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Review of high bandwidth fiber optics radiation sensors*

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Introduction

Fiber optics are being effectively utilized in an increasing range of data and information transfer applications. A less mature, but equally challenging, application of fiber optics concerns their use for a host of sensor technologies. Fiber sensors have now been developed for measurement of many physical parameters. These sensor systems frequently exploit several general attributes of fibers, including: cost, an all-dielectric transmission medium, freedom from electrical interference, bandwidth, resistance to degradation in severe or adverse environments, light weight, etc.

This paper summarizes the use of fiber optics or guided optical systems for radiation sensors. It is limited to passive systems wherein electrical power is not required at the sensor location. However, electrically powered light sources, receivers and/or recorders may still be required for detection and data storage in sensor system operation. This paper emphasizes sensor technologies that permit high bandwidth measurements of transient radiation levels, and will also discuss several low bandwidth applications.

In addition to discussion of several specific sensor concepts, an extensive bibliography is included to guide research into these, or other, forms of radiation sensors. The bibliography is subdivided into four major subdivisions. In the bibliography, each paper is listed only once, even though a given paper may include data appropriate to several sections. Furthermore, to avoid long reference lists within the text, only a few of the bibliographical entries are referenced therein. The present conference is not included in the reference list, but includes several related papers. Four other general reviews of related technologies may be of particular benefit.[1-4]

Radiation effects on optical fibers

At least six different radiation effects on optical fibers have been documented: (Some of the effects mentioned below are interrelated, in that one effect implies the existence of another effect.)

1) Dimensional Modifications - Extensive literature has documented alterations of material structure under irradiation.[60] Radiation can both cause defects in materials and, under some conditions, can serve to anneal defects. Such changes in microscopic structure can be anticipated to lead to dimensional or density modifications, and such effects in fibers have been documented.[58]

2) Refractive Index - A change in density or dimension will lead to a modification in refractive index. For example, Bertolotti, et al observed a change of 2.8% in refractive index in Pb-silicate core glass fibers after irradiation to 1000 rads.[58]

3) Thermoluminescence - Thermoluminescence is the basis for many simple radiation monitors using small chips or samples of several crystalline materials (e.g., LiF or CaF_2). This process relies on the creation of deep traps in a material subjected to radiation, the subsequent thermal release of trapped charges, and radiative recombination of these mobile charges at another site in the lattice. This radiative decay following recombination leads to an observable light output. Thermoluminescence has been observed and studied in optical fibers.[15,23]

4) Modal Properties - Light is transmitted within a fiber in specific modes, characterized by different spatial and angular distributions. Propagation characteristics of individual modes may be modified by radiation in several ways. For example, different modes preferentially propagate in different regions of a fiber. If radiation-induced absorption varies across a fiber (perhaps due to a gradient in fiber composition), modes will be affected to varying extents. The pulse dispersion characteristics of a fiber depend on the distribution of optical power among the

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modes in the fiber. Differences in radiation-induced attenuation of different modes[55] within a fiber have been documented, as have substantial changes in pulse dispersion.[57]

5) Absorption - Color centers are created during radiation exposure in optical fibers under irradiation. Extensive literature treats this phenomenon under many experimental conditions.

6) Luminescence - Both fibers and many other optical materials will emit light under irradiation. Again, very extensive literature addresses this phenomenon.

Processes 1-6 could be used for sensor applications. To the author's knowledge, processes 1, 2, and 4 have not been exploited as a sensor. Process 3 probably could be exploited, given a suitable sensor requirement. The last two processes have been extensively used and will be emphasized herein.

Both absorption and luminescence may occur either within a fiber (an "internal" sensor) or within a material adjacent to a fiber link (an "external" sensor). Both internal and external sensors are discussed in this paper. Furthermore, both phenomena may be used in high and low bandwidths systems.

Absorption and luminescence processes (number 3, 5 and 6) require intensity detection rather than phase-sensitive detection. Processes 1 and 2 could be used in a phase-sensitive mode. Process 4 might require a spatial mode detection system. All systems discussed herein use intensity detection.

Radiation sensors utilizing absorption phenomena

Alternative fiber compositions and draw conditions result in very large changes in both short- and long-term radiation-induced absorption. Many literature studies, particularly from the Naval Research Laboratory (NRL), document these differences.[1] For example, germanium-doped silica fibers demonstrate substantial transient absorption and a rapid recovery of the attenuation while phosphorus-doped fibers display less transient upset but very little recovery at long times. Both temperature (thermal annealing) and light level (photobleaching) are critical parameters in absorption observations.

At least three low-bandwidth fiber radiation sensor systems have been discussed in the literature. In 1977-78, an NRL package was flown on the Navigational Technology Satellite-2 and returned data on space radiation levels as a function of shielding for times in excess of one year.[47] A large "fiber" system was demonstrated using an FEP plastic tube with a dye solution of appropriate index as a core.[42,51-54] This dosimeter system has been extensively documented and has demonstrated useful performance over many decades of dose. A Pb-silicate core fiber was used in a civil defense dosimeter.[43] These systems benefit from a key attribute of fiber sensor systems in that the absorption phenomena scale with sensor length and wide ranges of dose may be studied with systems of varying length.

Transient absorption in fiber optics has been studied by several laboratories, including Los Alamos National Laboratory and the Naval Research Laboratory.[1,36,39] In principle, transient dosimetry measurements should be possible with fiber absorption sensors, but to the author's knowledge, successful systems have not been implemented.

Such systems concepts are complicated by two phenomena:

1. In most fibers, substantial recovery of transient absorption occurs on nanosecond time scales. Time-resolved dosimetry must deconvolve such recovery to determine the input radiation pulse time history. (Some fibers, notably phosphorus-doped fibers, would show minimal recovery and might be more suitable for transient dosimetry, but to date these fibers have not been studied on nanosecond time scales.)

2. Measurements of transient absorption for various dose levels have been reported on radiation resistant fibers.[39] These measurements have yielded a strongly nonlinear relationship between radiation dose and transient absorption magnitude.

Either one of these two phenomena would complicate accurate transient dosimetry using absorption in optical fibers. Taken together, they have discouraged the use of fiber absorption for transient dosimetry.

Absorption in optical materials external to optical fibers may also be considered. Radiation-induced optical absorption has been noted in many materials. One of the many possibilities would utilize hydrated (or solvated) electrons in aqueous solutions. Hydrated electrons offer a very fast (few psec), but insensitive, absorption mechanism.

Radiation sensors using luminescence phenomena

Fibers, as well as many other materials, can luminesce when exposed to ionizing radiation. These can form the basis for a wide range of sensor possibilities using luminescence internal or external to the fiber.

Both short- and long-term luminescence components have been identified from irradiation of optical fibers. Short-term components associated with pulsed, high energy, e-beam irradiation of fibers have been shown from wavelength and geometrical dependences to be dominated by Cerenkov radiation.[29] Calculations and measurements of Cerenkov light coupling coefficients for specific geometries are available in the literature.[10] Low-energy electron irradiations have also documented long-lived luminescence associated with fluorescence mechanisms.[17,49]

For sensor systems employing short lengths of fiber, degradation of the luminescence by fiber transmission limitations is not a serious concern. Many systems have used scintillating material, either plastic or various glasses, for fiber core material. Early systems of this type[30-35] relied on an air-plastic interface for light guiding, but more modern systems utilize cladding materials.[5,6,19] Arrays of short scintillating fibers have been extensively used in high energy particle physics research to localize ionization tracks. Conventional plastic scintillator films have been successfully used, together with coherent fiber bundles or arrays, to document space and time evolution of particle beams.[11]

For sensors systems requiring remote recording, the length of fiber can severely distort the observation. Both fiber attenuation and material dispersion complicate data transmission through long fibers. In addition, the small core area of high bandwidth fibers limits the amount of light coupled into propagating modes of the fiber. Both fiber attenuation and material dispersion are minimized for long wavelength systems. (As rough approximations, useful for wavelengths appropriate to "standard" scintillation materials (350-500 nm), these two phenomena scale with wavelength, λ, as λ^{-4} and λ^{-3}.) Unfortunately, Cerenkov light output scales as λ^{-3}, thereby yielding less light at the longer wavelengths of interest.

Considerable effort has been expended to utilize Cerenkov light as a radiation sensor, largely because it is an extremely fast process. Cerenkov light tracks the transit time of charged particles through the optical material. Material dispersion concerns were addressed in the first systems by using only a narrow spectral window in the system.[28] (Material dispersion over 1 km of fiber at 800 nm contributes about 110-120 ps of pulse dispersion per nanometer of spectral window). This only complicated the low sensitivity of these systems by rejecting most of the usable light.

Improvements have included three techniques:

1. Spectral Equalization - This development used a grating to disperse the Cerenkov pulse into various "equalizing" fibers, each fiber accepting a narrow (1 nm) spectral width. Each fiber was cut to a length, different for each fiber (and therefore, wavelength), to cancel material dispersion with fiber transit time. All equalizing fibers illuminated the final photodetector.[22]

2. Streak Equalization - This development dispersed the Cerenkov pulse onto the photocathode of a streak camera such that the direction of the sweep deflection was parallel to the wavelength dispersion axis. A sweep speed can be chosen to cancel material dispersion over a limited wavelength interval.

3. Both concepts, 1 and 2, have been combined into one system thereby allowing a more flexible choice of operating parameters.[9]

All three techniques have been used to varying extents. However, the first technique is more limited in speed by the use of a photomultiplier (~200 ps FWHM), whereas streak tubes (used in the latter two techniques) can be much faster. Recent improvements to (1) have now allowed it to use streak recording.

Special scintillators have also been developed to provide a light output useful with long fiber lengths. Both organic and inorganic scintillators have been studied to maximize light output efficiency, increase wavelength, and minimize time response.[16,18,20,24] These systems have been extensively used, frequently in conjunction with fiber/scintillator arrays to provide time and spatial resolution of a radiation source.

Conclusion

Fiber optic radiation sensors have been widely used in diagnostic applications. Future review papers on this subject will doubtless be more extensive than this effort, as more numerous and diverse applications of these technologies are documented.

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